PERFORMANCES AND FUTURE PLANS OF THE LHC RF

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Abstract

The ramp-up of the LHC operation has been exceptionally fast: from the first acceleration of a single bunch at nominal intensity (1.1E11 p) to 3.5 TeV/c on May 2010, to the accumulation of 11 fb^{-1} integrated luminosity two years later (June 2012). On the RF side this was made possible by a few key design choices and several developments, that allow reliable LHC operation with 0.35 A DC beam at 4 TeV/c (1380 bunches at 50 ns spacing, 1.5E11 p per bunch). This paper reviews the RF design and presents its performance. Plans are also outlined that would allow operation with 25 ns bunch spacing (doubling the beam current) and even increased bunch intensity with the target of above 1A DC current per beam, without big modification to the existing RF power system.

THE LHC RF

The LHC RF system consists of 8 RF stations per beam. The RF system accelerates the beam during the ramp, compensates the small energy losses during coasting, and also provides longitudinal focusing. A simplified block diagram of the LHC RF system is shown in Figure 1.

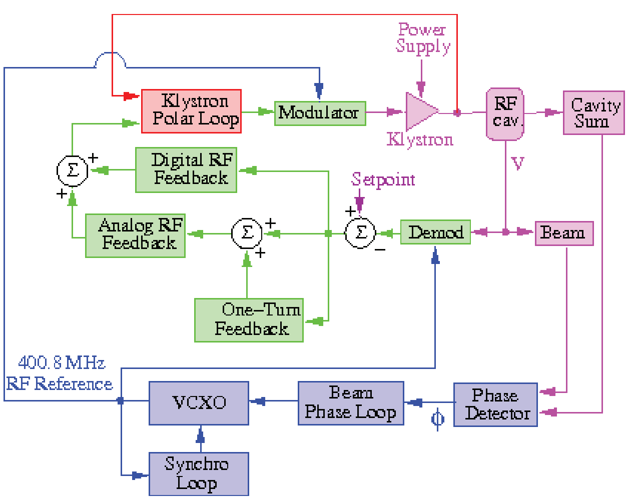

Figure 1: Simplified block diagram of the RF system. Cavity controller in green, beam phase loop in blue, klystron polar loop in red, and other RF components and beam in magenta.

Each RF station includes an accelerating superconducting cavity, a 330 kW klystron (currently operated with reduced DC settings limiting the power to 200 kW), and the Low Level RF (LLRF) system consisting of the klystron polar loop, the cavity controller, and the beam phase loop. The superconducting cavity has an *R/Q* of 45 Ω, a resonance frequency f_o of 400.8 MHz, and a mechanical tuner with a 100 kHz range. For nominal intensity beams, the cavity voltage V and loaded quality factor Q_L are set to 0.75 MV and 20,000 respectively during injection (flat bottom) and to 1.5 MV and 60,000 during collision (flat top). The cavity controller acts to compensate for the transient beam loading and to reduce the RF station fundamental impedance as sampled by the beam to increase longitudinal stability. It incorporates digital and analog paths, as well as the One-Turn feedback (OTFB), which acts to reduce the impedance at the revolution harmonics. The klystron polar loop (amplitude/phase) as implemented at the LHC acts to stabilize the klystron gain and phase response against variations due to high voltage power supply fluctuations and operation point (DC settings) changes. There is one klystron loop per cavity. The beam phase loop is a narrow bandwidth loop which acts on the Voltage-Controlled Crystal Oscillator (VCXO) to damp out barycentric longitudinal motion around the synchronous phase, motion driven by the noise in the RF system or by other mechanisms. There is one beam phase loop per ring. The beam phase loop averages the beam phase over all bunches in the ring.

CHALLENGES ON LHC RF OPERATION

The design and operational choices for the LHC RF were largely defined by the anticipated challenges and limitations due to the beam parameters and system specifications. The main challenges, the solutions implemented and their performances are outlined below.

Transient Beam Loading and Coupled-bunch Instabilities

The cavity characteristics greatly influence transient beam loading effects and coupled-bunch instabilities.

Filling in the LHC is done by the injection of up to twelve successive batches in each ring. During filling, the field in the empty buckets is perturbed by the beam in the filled buckets (transient beam loading). In the case of optimum detuning for the average beam current, and with a constant klystron drive, the peak phase modulation $\Delta\phi$ on the RF voltage caused be a beam gap is given by [1]

$$\Delta\phi \approx \pi f_0 \frac{R}{Q} \frac{I_{b,rf}}{V} t_{gap} \qquad (1)$$

where $I_{b,rf}$ is the RF component of the beam current, and t_{gap} the beam gap length. This phase modulation causes an injection phase error if the injection phase is kept constant, and results in capture losses. The effect is minimized by using superconducting cavities with a low *R/Q* (45 Ω) and high RF voltage. Furthermore, strong RF and One-Turn feedback systems were developed to keep

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the voltage constant over one turn during filling, ramping and in physics. The two systems manage to reduce the cavity phase modulation to the noise level, as seen in Figure 2. The transient beam loading caused by the 3 μs long abort gap is barely visible above the noise floor, resulting in 0.2 degree phase modulation only.

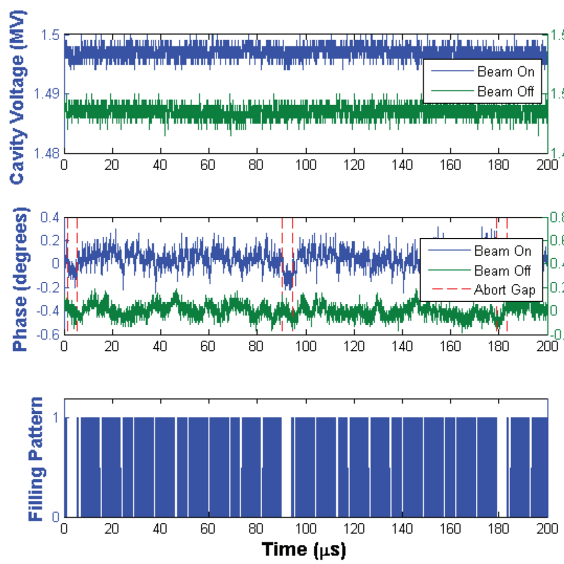

Figure 2: Cavity Voltage without beam and with 1380 bunches of 1.3E11 p/bunch, 50 ns spacing, and OTFB on, in physics. Y axes are shifted for the two data sets, but have the same scale.

The use of super-conducting cavities also minimizes the total impedance for a given RF voltage. There is no dedicated longitudinal damper in the LHC; longitudinal stability relies on Landau damping. There were concerns during the design phase on the coupled-bunch instabilities for such a high intensity (I_o > 0.5 A DC) machine. The narrow-band resonant impedance threshold R_{max} is given by [2]

$$R_{\max} \propto |\eta| \frac{E}{I_0} \left(\frac{\Delta E}{E} \right)^2 \frac{\Delta \Omega_s}{\Omega_s} \quad (2)$$

where η is the momentum compaction, E the beam energy, Ω_s the synchrotron frequency, and ΔE, $\Delta\Omega_s$ the energy and tune spread.

The design target was for an impedance below 0.9 MΩ at 7 TeV with 2.5 eVs longitudinal emittance. At the cavity fundamental resonance, with a Q_L of 60000, the total cavity impedance is 21.6 MΩ. Therefore, a reduction of the effective cavity impedance by up to two orders of magnitude was necessary. In the LHC, the combination of the RF and One-Turn feedback systems provides a factor of 300 reduction of the cavity impedance at the fundamental, more satisfying the design target.

Klystron Forward Power

The LHC RF design includes movable couplers to reduce the klystron forward power requirements. To achieve the constant RF voltage (in amplitude and phase) imposed by the strong RF feedback though, the klystron demanded power is different in the beam and no-beam segments. These power levels depend on the cavity tune. To reduce the *maximum* power requested during a turn, the "Half-detuning" scheme is employed in the LHC [3].

The "Half-detuning" scheme makes the demanded power equal during beam and no-beam portions. With the detuning

$$\left[\frac{\Delta f}{f_0} \right]_{half} = -\frac{1}{4} \frac{R}{Q} \frac{I_{b,\max}}{V_{acc}} \quad (3)$$

$$P_{beam} = P_{no\_beam} = \frac{1}{8} \frac{V^2}{Q_L R/Q} + \frac{1}{2} Q_L \frac{R}{Q} \left[\frac{I_{b,\max}}{4} \right]^2 \quad (4)$$

where $I_{b,max}$ is the RF component of the beam current in the beam segment.

Once the half-detuning policy is enforced, klystron power is uniquely dependent on the RF voltage, beam current and cavity loaded Q_L. The requested klystron power is, in theory, constant during the turn, although transients are observed in the transitions between beam and no-beam segments. The klystron drive is strongly phase modulated between the two segments. The LHC RF has been operated with this scheme since its start-up.

Beam Diffusion due to RF Noise

To prevent longitudinal emittance increase in physics due to RF noise, the emittance growth caused by RF noise should remain below the synchrotron radiation damping time (13 hours at 7 TeV). The multiple RF loops (cavity controller, klystron polar loop, beam phase loop), achieve very low levels of RF noise in the LHC system. Figure 3 shows the phase noise of the RF sum of the eigth cavities. The blue trace is measured without beam.

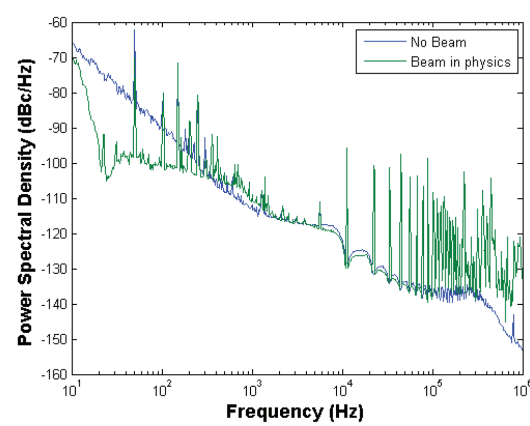

Figure 3: Cavity sum phase noise power spectral density in dBc/Hz. Physics conditions (12 MV). No beam (blue) and with beam (green).

In the lower frequency range (10 Hz–1000 Hz), the noise is dominated by the VCXO characteristics. The slope (-20 dB/decade) is related to the quality factor of the crystal oscillator. The various lines (50 Hz and harmonics) come from the klystron HV ripples. The klystron polar loop reduces them by 50 dB minimum up to 600 Hz. Reduction of 50 Hz and harmonics is very

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important as the synchrotron frequency varies between 55 Hz at injection and 26 Hz in physics. It crosses 50 Hz during the ramp. In the high frequency range (10 kHz-400 kHz), the spectrum is rather flat at -135 dBc/Hz. It is dominated by the noise of the cavity antenna demodulation, used as measurement by the RF and One-Turn feedback loops. The trace shows dips at the multiple of the revolution frequency (11 kHz). This noise reduction is the contribution of the OTFB that increases the regulation gain at these frequencies.

The green trace shows the RF noise with beam. The beam phase loop reduces the noise spectrum at the synchrotron frequency (26 Hz in physics) by at least 30 dB. It does not affect the spectrum above 1 kHz. Without this loop there would be no physics: the VCXO phase noise around 26 Hz (-75 dBc/Hz) would reduce lifetime below one hour. The lines at harmonics of the revolution frequency (11 kHz) come from the small uncompensated transient beam loading.

With the significant noise reduction, the RF caused bunch lengthening (4σ) was estimated at 2.5 ps/h in 2011 at 3.5 TeV, without the OTFB, for a bunch length of 1.25 ns [4]. In 2012, with the OTFB on, the effect of noise on beam diffusion is even lower. A typical fill is shown in Figure 4. There is a transient when the beams are put in collision, lasting for about 30 minutes. Then the growth rate, dominated by Intra-Beam Scattering (IBS) decreases gently from 30 ps/h down to 8 ps/h towards the end of the nine hours long fill.

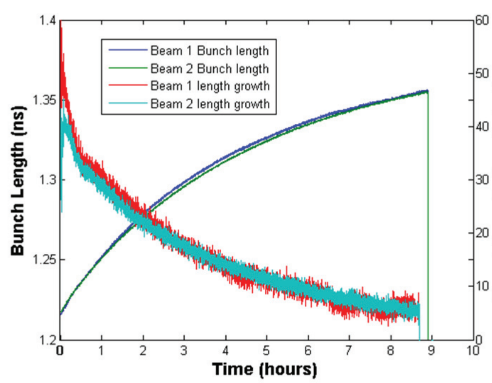

Figure 4: A typical fill in 2011: 1380 bunches. 1.3E11 p/bunch, 1m β*, 3.5 TeV conditions with fixed 12 MV RF.

RF noise was a major concern during the LHC design. It has been successfully reduced to a level that is no more an issue for LHC operation.

Broadband Longitudinal Stability

There is no dedicated longitudinal feedback system in the LHC and stability is only achieved through Landau damping. Therefore, it is essential to maintain sufficient synchrotron tune spread during the LHC cycle. The broadband longitudinal impedance threshold is given by

$$\frac{|\mathrm{Im}\,Z|}{n} < \frac{|\eta| E}{eI\,\beta^2}\left(\frac{\Delta E}{E}\right)^2 \frac{\Delta\Omega_s}{\Omega_s} f_0 \tau \propto \frac{\varepsilon^{5/2}}{E^{5/4} V^{1/4} I} \propto \frac{\tau^5 V}{I} \qquad (5)$$

where Z is the longitudinal impedance, e the particle charge, τ the bunch length in time, I the single bunch current and ε is the longitudinal emittance [2].

Bunches are injected into the LHC with a bunch length of about 1.4-1.5 ns and a longitudinal emittance of 0.5 eVs. During the ramp, the RF voltage is increased twofold. To prevent loss of single-bunch stability, the longitudinal emittance has to be increased during the ramp, as seen in Equation (5). The longitudinal blowup implemented in the LHC keeps the bunch length constant [5][6], so that the single-bunch longitudinal stability threshold increases linearly with the RF voltage making the situation more stable at higher energy.

The blowup algorithm injects band-limited RF phase-noise in the main accelerating cavities. The noise-band starts at 0.85 Ω_s and extends to 1.1 Ω_s to limit the excitation to the core of the bunch. The digitally created noise tracks the synchrotron frequency change during the energy ramp. The noise amplitude is controlled by a feedback algorithm monitoring the measurement of the average bunch-length over each ring [5].

Operational Parameters

Bunches of 0.5 eVs (1.4-1.5 ns bunch length) are injected to the LHC from the SPS. The capture voltage is set to 6 MV (1.24 eVs bucket area) to minimize capture losses (below 0.5%). Figure 5 shows the SPS and LHC buckets, as well as the estimated bunch size at injection. Also shown is the SPS 1.05 eVs contour that is the smallest bucket area during the SPS ramp. 1380 bunches are injected per beam. The bunch intensity has been slowly increased in the 2011 and 2012 runs, passing 1.6E11 p/bunch (0.4 A DC).

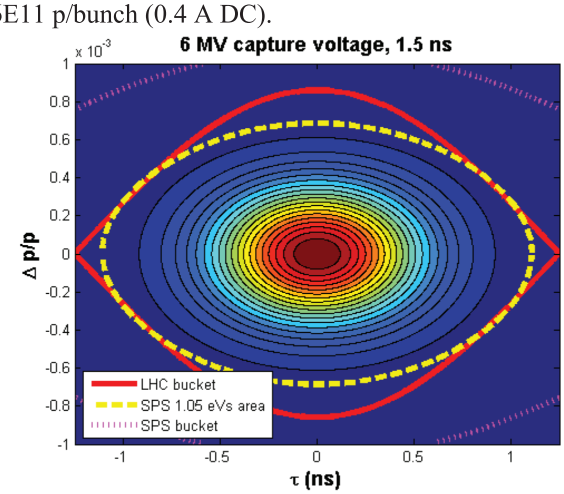

Figure 5: SPS and LHC bucket areas, and estimated bunch size at injection. Contours spaced by 5% intensity.

During the ramp, the RF voltage is raised linearly from 6 MV to 12 MV. The couplers are moved from the Q_L = 20k position to a value of 60k. With the longitudinal blowup, the emittance is increased to 2.5 eVs. In physics the lifetime is limited by IBS and beam-beam effects. To limit transverse emittance growth (and resulting drop in luminosity), the longitudinal emittance must be maximized. This is achieved with an RF voltage at

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12 MV (5.2 eVs bucket area). With the 0.4 A beam current, 155 kW/klystron are needed.

LHC PERFORMANCE

The LHC and its injectors have been performing exceptionally well. The peak luminosity at 4 TeV has already reached 70% of the design value at 7 TeV. Improvements in peak luminosity during 2012 are mainly due to the increase in bunch intensity. We have reached 1.6E11 p/bunch for a design value of 1.15E11 p/bunch. The integrated luminosity in 2012 has surpassed expectations. Almost 15 fb^{-1} have been integrated in CMS and ATLAS so far in 2012 (5 fb^{-1} in 2011).

FUTURE CHALLENGES

The LHC RF is performing very well presently. There are various developments and upgrades in plan for operation with higher bunch intensity, higher total beam current, 25 ns spacing, damping of longitudinal oscillations at injection and asymmetric beams (operation with protons colliding lead ions).

High Single Bunch Intensity

In 2011, up to three bunches 2.85E11 p/bunch were captured and circulated at 450 GeV with the usual 6 MV RF. Injections were performed with the beam phase loop on and off. No sign of longitudinal instability were observed through monitoring of the individual bunch phase and bunch length.

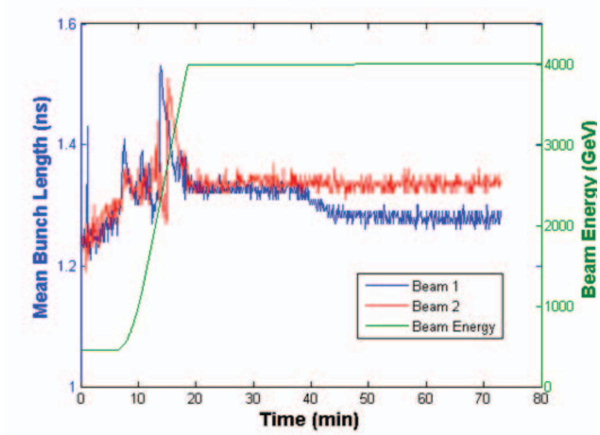

Figure 6: Bunch length during ramp for single bunches with high bunch intensity.

In 2012, two bunches per ring, with 3E11 p/bunch, were successfully ramped to 4 TeV. The bunch length at the end of the ramp was about 1.35 ns through the longitudinal blow-up action (target was set at 1.4 ns), as shown in Figure 6. The beam phase loop was on. There were small transmission losses during the ramp (< 2 %). With these tests, it was evident that there is no RF issue with high bunch intensity as long as the beam phase loop is on and the longitudinal blowup is activated during the ramp.

25 ns Spacing and Klystron Power

As described above, a lot of klystron power is required to cancel cavity beam loading effects. Klystrons will saturate in physics for LHC beams above nominal (1.15E11 p/bunch, 25 ns spacing). Therefore, a new scheme has been developed.

In physics, the modulation of the cavity phase by the beam current (transient beam loading) will be accepted, by appropriately adapting the voltage set point for each bunch. Thus, the klystron drive will be kept constant (amplitude and phase) over one turn, without loss of the strong RF and One-Turn feedback action. The cavity will be detuned so that the klystron current is aligned with the average cavity voltage. With this scheme, the needed klystron power becomes independent of the beam current [3][8]. For a Q_L of 60k, only 105 kW would be needed for an RF total voltage of 12 MV.

Since it is desirable to keep the cavity phase constant for clean capture during injection, the new scheme will only be activated at the end of the injection phase. The total voltage is reduced at injection (6 MV); therefore there is no limitation with the klystron power at injection with the present scheme.

The new scheme has already been tested with very promising results. Figure 7 shows the resulting cavity phase modulation (green) compared to the situation with the present fixed voltage scheme (blue). For ultimate beams (1.7E11 p/bunch, 25 ns spacing), this modulation would reach 60 ps along the ring. The effects to the collision point should be negligible though, since the variation is symmetric for the two rings, thereby cancelling at IP1 (ATLAS) and IP5 (CMS). Beside the 60 ps modulation is very small compared to the bunch length of 1.25 ns.

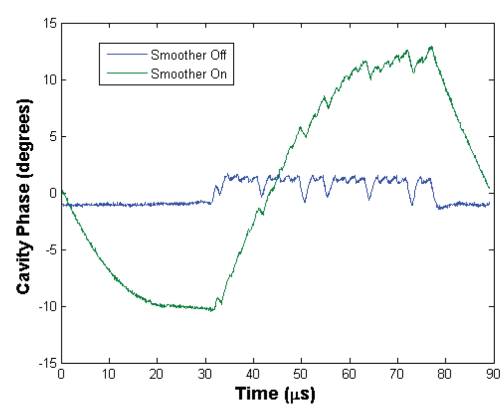

Figure 7: Cavity phase with setpoint adaptation for beam loading effects. OTBF off.

Transverse Emittance Preservation

About 30 minutes are needed to fill both LHC rings, with 12 batches per ring. The batches injected first suffer from transverse emittance growth (caused by IBS) resulting in a reduced luminosity when put in collision. It is possible to reduce the IBS effects on transverse emittance by increasing the longitudinal emittance of the newly injected batch after each injection. Tests are in

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progress of this batch-by-batch longitudinal blowup at injection scheme.

Coupled-bunch Instabilities

Models and simulations of the LHC RF system interaction with the beam have been developed to estimate the coupled-bunch oscillation growth rates at 7 TeV and ultimate LHC beam currents. Realistic cavity configurations using the experience from LHC operation were used. Significant stability margins are anticipated with ultimate beam, even with the OTFB off [7]. The sensitivity to LLRF parameters was investigated, suggesting a large dependence of the longitudinal growth rates on the RF and One-Turn feedback phase. Even a 10 degree variation of these phases would not lead to an unstable beam though. The situation when the cavity detuning crosses the revolution frequency, encountered with the scenario proposed in [8], was also investigated. No critical situations for beam stability were discovered in this case either.

Longitudinal Damper

There is no dedicated longitudinal kicker in the LHC. Therefore, the longitudinal damper will act through the RF cavities to reduce injection oscillations, by modulating the RF phase in the 1 μs gap between circulating and incoming batch. A 50 kV step can be achieved in this time from *each* cavity, leading to a maximum momentum kick of 0.4 MeV/c per turn or 80 MeV/c per synchrotron period at 450 GeV. A reduction of the energy error by a quarter of the bucket half-height can be thus achieved in one synchrotron period. The longitudinal damper will be tested during the 2012 run, to be ready for operations with 25 ns beam after the first LHC long shutdown.

Asymmetric Beams (Proton-Pb Ion Operation)

Operation with asymmetric beams required some further development in the LLRF. With asymmetric beams, the two LHC rings see identical strength but opposite sign magnetic field. The RF systems are independent for the rings, with a 4.7 kHz difference between the two 400 MHz RF at injection. At the end of the ramp the difference is 60 Hz only. On flat top the two rings are locked on the same frequency, resulting in a +0.3 mm offset of the p ring and -0.3 mm offset of the Pb ring. The two rings are then gently cogged to achieve crossing in the detector. This process requires eleven minutes, worst case, to rotate the crossing point over the full 27 km long LHC. First collisions were achieved on Sept 13^{th}.

CONCLUSIONS

The LHC RF system has performed very well during the first phase of the LHC operation. Various systems and algorithms have been developed to overcome or push the limitations on the LHC performance. Upgrades and developments for future high intensity are already in progress and are providing encouraging results.

ACKNOWLEDGMENTS

More than twenty colleagues in the BE-RF group have contributed to the success of the LHC RF and I wish to thank them all. The many discussions with E. Shaposhnikova and J. Tuckmantel have been very helpful to better understand the LHC stability issues and beam-cavity interaction. They have also proposed the method used in the longitudinal blow-up and the one being implemented for adaptive cavity phase modulation. J. Molendijk has been leading the LLRF firmware designs from the start in 2005. His contribution made it possible to transform many smart ideas into reliable operational implementations. We thank A. Butterworth, responsible for the RF high level controls, who finally turns our innovations into something useful for machine operation. Our relations with the LHC operation team have been excellent from the LHC start-up in September 2008 and still are. We thank them for their competence, motivation and support during both machine development sessions and machine operation. It has always been a pleasure to step into the LHC Control room, even when the machine was not in its best shape. During the past four years of RF commissioning we have had the time to appreciate the choices made by the LHC RF original designers D. Boussard and T. Linnecar. They made our task (almost) easy. The close interaction with the representatives of the four main LHC experiments has been extremely motivating. We thank them for constructing this excellent working relation.

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